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COMMUN. SOIL SCI. PLANT ANAL., 26(19&20), 3145-3163 (1995)

AERIAL DRY MATTER AND NUTRIENT ACCUMULATION COMPARISONS AMONG FIVE SOYBEAN EXPERIMENTS

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ABSTRACT: Efficient and environmentally acceptable nutrient management requires an understanding of when and at what rates nutrients are accumulated by plants. For graminaceous species, a mathematical procedure involving compound cubic polynomials was previously demonstrated to be useful for evaluating growth and nutrient accumulation patterns. Our objective for this study was to compare dry matter and nutrient accumulation rates for determinate and indeterminate soybean [*Glycine max* L. (Merr.)] by reanalyzing the original data from five field experiments. Data from a maximum yield research (MYR) experiment that yielded 6.8 Mg ha^{-1} provided information for soybean grown with near-maximum accumulation rates. The high MYR yield resulted from intensive management practices that included high fertilization, high plant population, complete pest control, and timely irrigations to supplement rainfall. The MYR results were compared with rates determined for four non-MYR studies that yielded from 2.2 to 5.4 Mg ha^{-1} in Iowa, South Carolina, and North Carolina. Contrary to patterns found for corn (*Zea mays* L.) and wheat (*Triticum aestivum* L.), no consistent, distinct peaks in accumulation rate were observed for soybean. Instead, trends

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were masked by short-term variation caused either by responses to environmental variation or by random sampling errors. In addition, computed maximum growth rates for the 6.8 and 5.4 Mg ha^{-1} studies were higher than the hypothesized maximum rate of 360 kg ha^{-1} d^{-1}, suggesting either biased sampling or a need to reexamine the theory. These findings lead us to conclude that further research in intraseasonal accumulation patterns for soybean should concentrate on causes for short-term variation, such as weather patterns, via mechanistic simulation. Further, the data for extremely high yields should be considered cautiously until supporting data are found.

INTRODUCTION

Environmental and economic pressures on farmers and agribusiness emphasize the importance of applying plant nutrients in the most efficient and timely manner possible. To accomplish this goal, it is essential to quantify and understand effects of crop and soil management practices on amounts and rates of dry matter and nutrient accumulation.

A review of the soybean literature identified five studies in which dry matter and nutrient accumulations were reported. Henderson and Kamprath (1) and Scott and coworkers (2,3,4,5,6) provided data for two determinate soybean cultivars in the Carolinas. Dunphy (7) and Mason et al. (8) reported data for indeterminate soybean in Iowa. A fifth data set was located in the popular press (9) and supplemented with additional information from the editor (W. Griffiths, 1992, personal communication). These data sets varied somewhat, such as cultivar and nutrients analyzed, but from each data set, aerial dry matter and nutrient uptake could be calculated. The five data sets also varied in sampling frequency and presentation method (amounts vs. concentrations, rates vs. totals), which complicated comparison among uptake rates. Therefore, we re-analyzed all data sets to compute uptake rates using a single, consistent method.

Use of compound cubic polynomials (splining) to describe plant growth and nutrient accumulation data was compared to other interpolation techniques by Sadler and Karlen (10). They had used splines to describe aerial dry matter and nutrient accumulation for corn (11) and soft red winter wheat (12) in the southeastern Coastal Plains of the USA. The fundamental difference between describing accumulation data with compound cubic polynomials and with a least squares statistical approach is that splining can identify periods of intraseasonal variation in accumulation, whereas regression techniques smooth through variation. Splining requires an assumption that data variation is real, meaning that the intraseasonal variation can be explained by changes in weather pattern, plant growth stage (i.e., vegetative vs. reproductive), or by other factors affecting crop growth and development. If data are highly variable, intraseasonal fluctuations may be exaggerated.

Application of the splining technique to describe dry matter and nutrient accumulation patterns for a legume is available only in an industry workshop proceedings (13). Those preliminary analyses suggested that accumulation patterns for soybean might be different than previously identified for corn and wheat, presumably because soybean has capacity for symbiotic N_2 fixation and can have either a determinate or indeterminate growth pattern. Those analyses were expanded by adding two additional indeterminate soybean data sets from Iowa (7,8).

The objective of this study was to compare rates of dry matter and nutrient accumulation for five soybean data sets that had yields ranging from 2.2 to 6.8 Mg ha^{-1}.

METHODS AND MATERIALS

Four soybean data sets were taken from the literature and were supplemented with one data set published only in the popular press (9). A brief description of each experiment is presented in Table 1.

For this analysis, information on 'Lee' and 'Bragg' soybean will be referred to as NC67 and SC79. Both data sets provided aerial growth and nutrient accumulation for determinate soybean cultivars that were grown using recommended production practices. Information for 'Hark' and 'Amsoy' soybean provided aerial

TABLE Descriptions of five soybean field experiments for which nutrient accumulation data were determined.

Location	Year, Sow Day§	Cultivar	Soil type†	Row width	Yield	Source	Nutrients measured‡												
				m	Mg ha^{-1}		N	P	K	Ca	Mg	S	Al	B	Cu	Fe	Mn	Na	Zn
Clayton, NC	1967 130	Lee	Norfolk ls	1.07	5.4	(5)	+	+	+	+	+								
Boone, IA	1971 134	Hark, Amsoy	Webster sil	0.76	2.8	(2)	+	+	+	+	+	+	+	+	+	+	+	+	+
Castana, IA	1979 135	Wayne	Ida sil	1.00	2.5	(13)	+	+	+	+	+		+	+	+	+	+	+	+
Florence, SC	1979 143	Bragg	Goldsboro ls	1.00	2.2	(17)	+	+	+	+	+					+	+		+
Adelphia, NJ	1985 149	Asgrow A3127	Freehold ls	0.15	6.7	(4)¶	+	+	+	+	+	+		+	+	+	+		+

† Soil abbreviations: ls=loamy sand, sil=silt loam

‡ + means the element was measured, blank means it was not measured.

§ Day of year at sowing.

¶ And R. L. Flannery, 1992, personal communication.

growth and nutrient accumulation data for indeterminate cultivars that will be referred to as IA71 and IA79.

The highest known soybean yield (6.8 Mg ha^{-1}) with corresponding plant nutrient data is from a study published only in the popular press and herein will be referred to as NJ85. Details for that experiment were not presented in Flannery (9), so they are presented here. Indeterminate 'Asgrow[2] A3127' soybean was grown on Freehold (fine-loamy, mixed, mesic Typic Hapludult) loamy sand near Adelphia, NJ, in 1985. A population of 506 000 plants ha^{-1} was grown in 0.15-m rows with 168-99-276-1-6-28-6 kg of N-P-K-B-Cu-Mn-Zn ha^{-1}. The insecticide diazinon [(*O,O*-Diethyl *O*-(2-isopropyl-4-methyl-6-pyrimidinyl) phosphorothiote)], a seed-applied fungicide captan (*cis*-*N*-Trichloromethylthio-4-cyclohexene-1,2-dicarboximide), the herbicides trifluralin (α,α,α-Triflurono-2,6-dinitro-*N,N*-dipropyl-p-toluidine) and imazaquin (2-{4,5-dihydro-4-methyl-4-(1-methylethyl)-5-oxo-1*H*-imidazol-2-yl}-3-quinoline carboxylic acid)], supplemental irrigation, and the foliar-applied fungicide benomyl (Methyl 1-{butylcarbamoyl}-2-benzimi-dazolecarbamate) were applied at labeled rates. The objective was to remove as many constraints as possible so that the crop could express its genetic potential yield. Drought stress was minimized by applying water through double-wall trickle irrigation tubing. Irrigation totaling 23 mm supplemented the 610 mm of rain between 22 April and 15 October. At early bloom and early pod-fill, part of the fertilizer was injected through the irrigation system.

Because sampling procedure has been shown to affect both precision and bias in soybean dry matter measurements (14), sampling strategies used for these experiments are outlined here. The NJ85 data consist of four whole-plant samples from each of four replicates. The NC67 data set represents whole-plant samples as well, starting with 20 plants per plot, and decreasing to 5 to 10 plants as the size of

[2]Mention of a trademark, proprietary product, or vendor does not constitute a guarantee or warranty of the product by the USDA, and does not imply its approval to the exclusion of other products or vendors that may also be suitable.

the plant increased (1). The IA79 data set for each plot represented 10 plants early in the season, 6 plants later, and 10 plants again at harvest (8). The SC79 data set consisted of four plants from each of 16 0.3-m^2 areas per treatment (3). The IA71 sampling procedure was to harvest all plant tops from a 1.52-m length of outside row, from which eight representative plants were chosen (7).

In each of these five experiments, replicated whole-plant samples were collected a total of from 6 to 13 times. Samples were fractionated into leaves, stems, petioles, and pods + seeds; dried to determine aerial dry matter amounts; ground; and analyzed to measure the nutrients indicated in Table 1. Accumulation was calculated for each sampling date and fraction, and summed to determine total aerial accumulation. These data were fitted mathematically using compound cubic polynomials (10). The interpolant polynomials were differentiated to determine rates of dry matter and nutrient accumulation. Values for dry matter, N, P, and K were plotted as a function of days after planting for comparison among experiments. Similar evaluations were made for secondary and micronutrients, but these contributed very little to this discussion and were therefore omitted for brevity.

RESULTS AND DISCUSSION

Seasonal weather patterns for Clayton, NC (1967), Florence, SC (1979), Boone, IA (1971), Castana, IA (1979), and Adelphia, NJ (1985) are shown in Figures 1 and 2. These illustrate growing conditions for the five soybean crops. The high NC67 yield indicates that conditions were favorable, in spite of a period of low rainfall between day of year 145 and 180, which corresponds to DAP 10 to 50. The SC79 rainfall data were not representative of the water available to the crop, because 244 mm fell between September 4 and 8, during and immediately after Hurricane David (3). This weather event probably contributed to the low yield (2.2 Mg ha^{-1}), because rainfall and wind from the hurricane decreased plant height and leaf area index during pod-fill, and appeared to increase abortion of pods and seeds, perhaps because of reduced aeration.

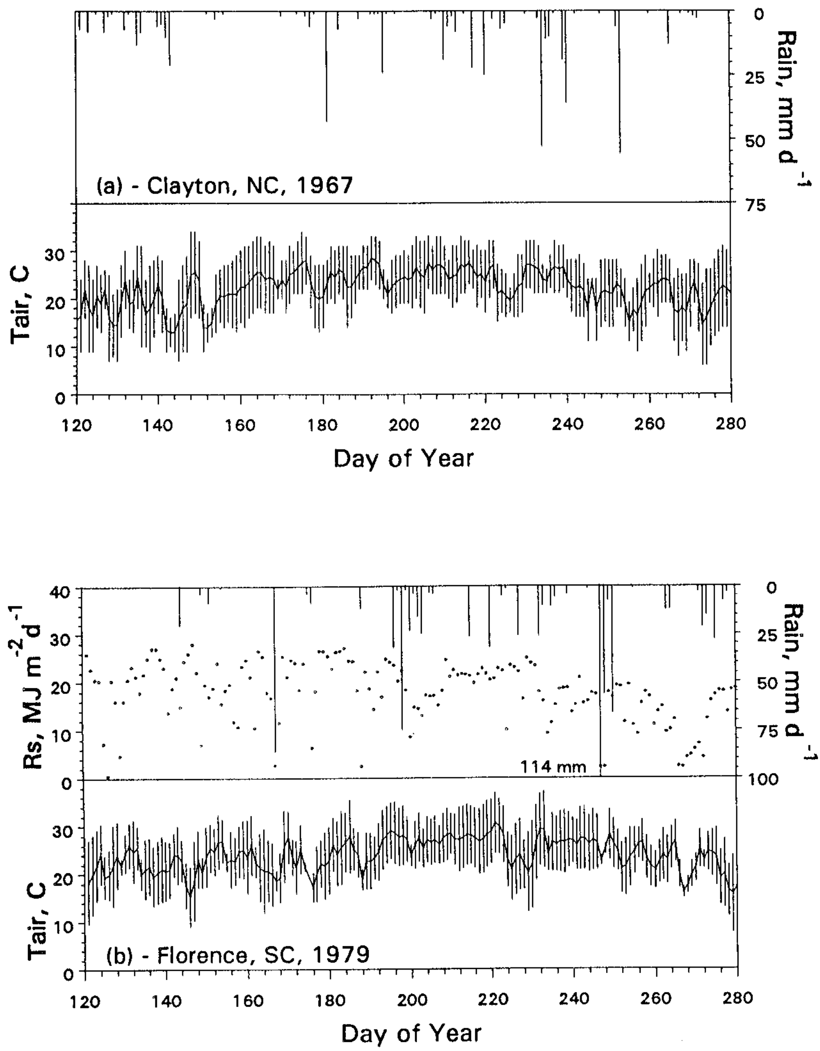


FIGURE 1. Weather patterns for (a) Clayton, NC, and (b) Florence, SC, where dry matter and nutrient accumulation for determinate soybean were measured. Rain includes irrigation, Rs is solar irradiance, and Tair is air temperature.

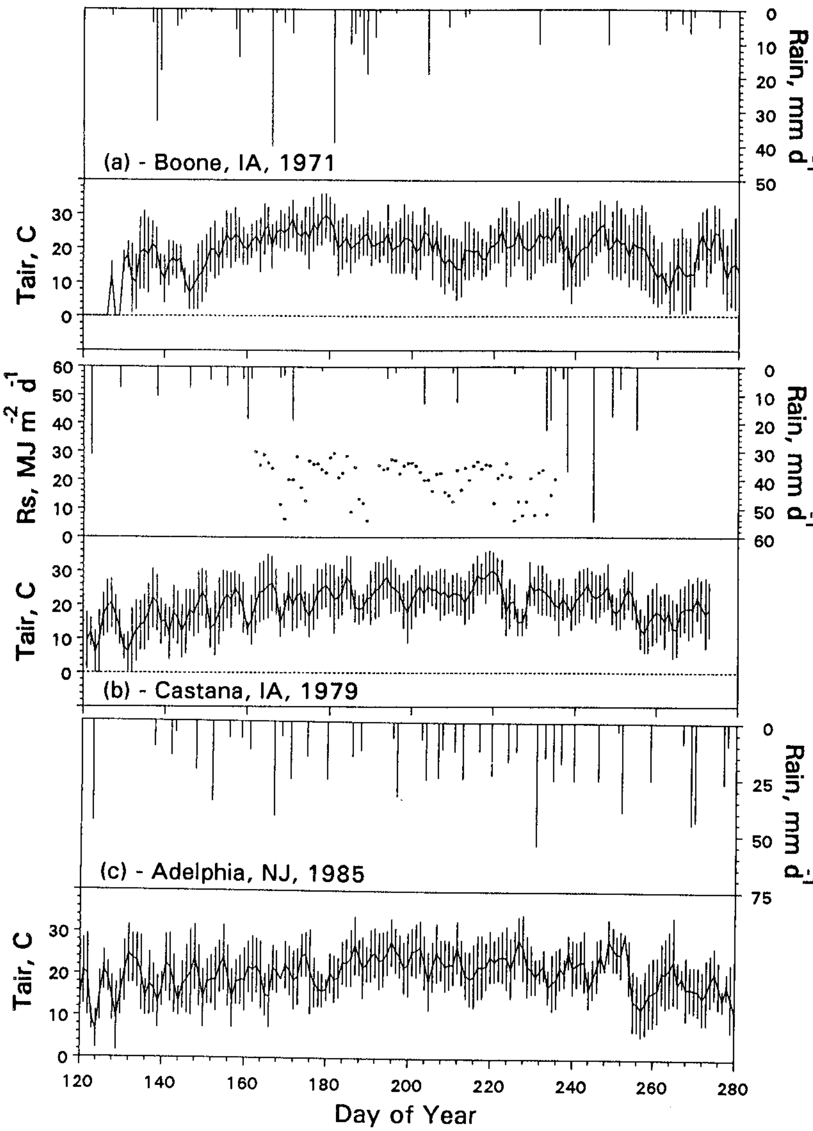


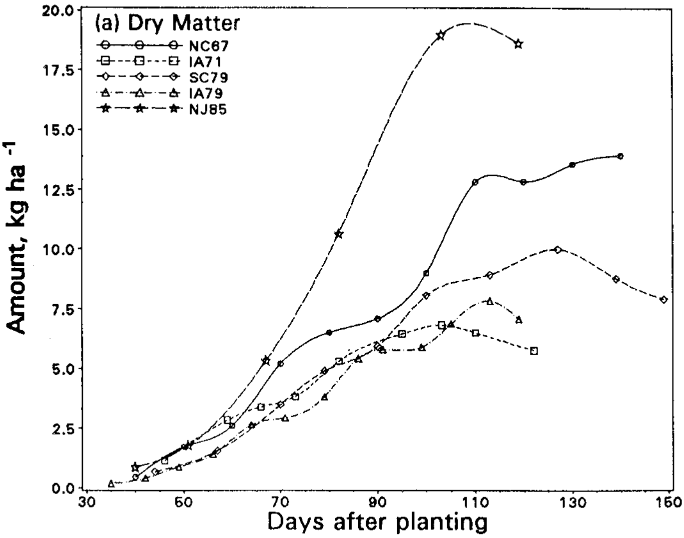
FIGURE 2. Weather patterns for (a) Boone, IA, (b) Castana, IA, and (c) Adelphia, NJ, where dry matter and nutrient accumulation for indeterminate soybean were measured. Rain includes irrigation, Rs is solar irradiance, and Tair is air temperature.

Weather data for the Iowa studies (Fig. 2a, 2b) appeared to be normal, and since there was no yield response to irrigation for IA79 (8), we assume the soybean crop had sufficient water. Furthermore, temperature and mid-season solar radiation appeared typical. Weather records for NJ85 (Fig. 2c) show generally moderate temperatures, and, on average, either rainfall or irrigation occurred every 3 days, so it is probably safe to assume that the crop was well-watered.

Amounts and rates of aerial dry matter accumulation by soybean grown in these five studies are presented in Fig. 3. Maximum dry matter accumulations for the IA71, SC79, and IA79 crops were 6.8, 7.8, and 10.0 Mg ha^{-1}, respectively. The NC67 crop that yielded 5.4 Mg ha^{-1} (1) had 13.9 Mg ha^{-1} of aerial dry matter, while the NJ85 crop that yielded 6.8 Mg ha^{-1} accumulated 19.0 Mg ha^{1}. Accumulation patterns were similar for all five crops, although the determinate cultivars reached their peak approximately 120 days after planting (DAP), while the indeterminate cultivars reached their peak approximately 100 DAP. This was approximately Growth Stage 9 (15) for both indeterminate and determinate cultivars.

Dry matter accumulation rates (Fig. 3b) fluctuated more over the short term than was observed for corn or wheat (11,12). This suggests that a) statistical noise overcomes temporal variation in growth rate, or that b) soybean growth patterns were more responsive than corn or wheat to temperature, to radiation, or to short-term rainfall and changes in surface soil water content for most of the season. One cannot distinguish between these two possibilities with the data sets alone. Were it possible to simulate growth rates with sufficient sensitivity to weather, one could address whether this variation is stochastic or deterministic.

Maximum derived accumulation rates were 442, 183, 253, 237, and 478 kg ha^{-1} d^{1} for the NC67, IA71, IA79, SC79, and NJ85 studies, respectively. The maximum rates of dry matter accumulation in the NC67 and NJ85 experiments are higher than the reported theoretical maximum productivity for soybean (K. J. Boote, 1992, personal communication). Sinclair and Horie (16) reviewed crop radiation-use efficiency and concluded that unstressed soybean would produce 1.2 g biomass MJ^{-1}



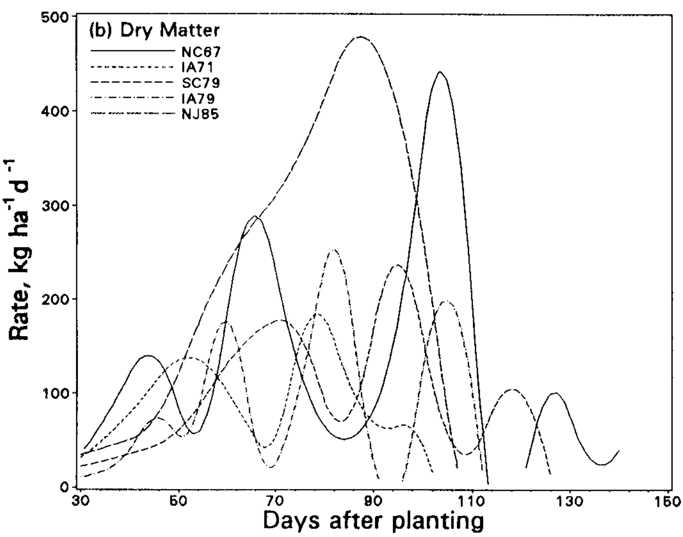


FIGURE 3. Amounts (a) and rates (b) of aerial dry matter accumulation for five soybean data sets.

intercepted radiation. Assuming a daily radiation total of about 30 MJ m^{-2} d^{-1}, and assuming that all radiation was intercepted (probably a safe assumption, given the planting density), then 360 kg ha^{-1} d^{-1} would be the theoretical maximum dry matter accumulation rate. As seen in Fig. 3b, the NJ85 data exceed that from about 76 to 96 DAP, with a maximum of 478 kg ha^{-1} d^{-1} on DAP 87. Additionally, the NC67 data exceeds the maximum for about a week. Consequently, it is important to consider the possible sources of error in order to interpret the results for such data. One important source of error when differences are taken is that opposing, random errors can compound in the subtraction. If an overestimate were to follow an underestimate, then the rate, computed from the difference, would be doubly increased. Consider the NC67 data first. If one assumes that random variation in sampling occurred such that the value at DAP 110 was a slight overestimate, then the average rate for the period from DAP 100 to 110 would be very similar to the rate for the adjacent periods. One could imagine a ~10% overestimate at DAP 110, followed by a smaller underestimate at DAP 120, but there is no way to ascertain whether this actually occurred.

Such analyses cannot be used to explain two consecutive high points, such as exhibited in the NJ85 data at 82 and 103 DAP. While the high rate between DAP 67 and 82 could partially be due to an overestimate at DAP 82, one would have to hypothesize an even larger, less probable, overestimate at DAP 103 in order to create the high rate between DAP 82 and 103. Therefore one must examine other potential causes of errors, such as the limited sample size. Sampling errors in four-plant samples were analyzed by Hunt et al. (14), who obtained a 42% overestimate over the whole plot mean. They hypothesized that even random samples taken in a plot are biased toward areas that look better, simply because of the elimination of poor areas for sample collection. If the two data points in question are biased upward on the order of 40%, then the average rates for the period from DAP 67 to 103 falls to about 227 kg ha^{-1} d^{-1}. The average rate for the raw data between DAP 67 and 82 is 355 kg ha^{-1} d^{-1}. Assuming a 40% upward bias for all samples reduces this to 213 kg ha^{-1} d^{-1}. If the theoretical upper limit of 360 kg^{1}ha^{1} d is real, then one must hypothesize significant multiple sampling errors to explain these data. These conjectures are impossible to confirm or deny, but are offered as a caveat to facilitate interpretation of results that have been questioned but not analyzed with objective procedures. The New Jersey data were included because the results are fairly well known from conference proceedings and the popular press. Rather than ignore this unrefereed information, we compared it to published data. This analysis illustrates problems with the data that have been suspected but remain unproven by objective methods. (For the record, the full set of raw data are no longer available. The variances for concentrations still exist, but not those for dry matter.)

The high rates were not created by 'noise' introduced into the data by the interpolation technique. As is described in Sadler and Karlen (10), it simply draws a line through the data. The derived rate is the value required to connect the points with that line. Using the technique implies two assumptions: a) that the data are unbiased representations of real dry matter and nutrient amounts, and b) that the stiffness of the curve approximates the degree of autocorrelation in the data. The first assumption may be compromised by bias or random errors in sampling. The second, that rates from day to day are somewhat related, can be justified by the continuity of the plant size, plant condition, and similarity of daily weather. Whether the stiffness of the spline causes the line to exactly match the intervening, unmeasured data is difficult to test.

Henderson and Kamprath's (1) report provides an opportunity to compare the splining method with the traditional approach for determining accumulation rates. They presented aerial dry matter and nutrient accumulation rates for the NC67 crop that were calculated by dividing the growing season into three periods (40-60, 60-100, and 100-110 DAP). The NC67 rate curve (Fig. 3b) has local maxima of aerial dry matter accumulation during each of those three periods. Average dry matter accumulations for those periods, using the traditional approach, were 106, 162, and 380 kg ha^{-1}, respectively. As expected, splining predicted higher peak values (140, 289, and 442 kg ha^{-1}), but the two methods, by definition, result in numerically equal average values. Both higher peak values for splining and correspondence of average rates were also confirmed for corn (17).

Fluctuation and possible errors in estimating dry matter accumulation would also affect calculated amounts and rates of nutrient accumulation. However, if splining can identify consistent patterns among the data sets, as previously demonstrated for corn (11) and wheat (12), the information may be useful for improving nutrient use efficiencies and perhaps reducing the potential for loss of plant nutrients from the crop root zone. Nitrogen accumulation (Fig. 4) during the first 70 DAP was similar for all five data sets. It remained similar for the IA71, IA79, and SC79 studies, which had maximum accumulations of 198, 221, and 242 kg ha^{-1}, respectively. Maximum N accumulation was 462 kg ha^{-1} for the NC67 crop and 615 kg ha^{-1} for the NJ85 study. The maximum N accumulation of 615 kg ha^{-1} exceeded applied N by 447 kg ha^{-1}. This difference was presumably supplied by N_2 fixation, although residual soil N from the previous MYR corn crop may have contributed. The maximum N accumulation rates were 8.2, 5.7, 5.9, and 4.9 kg ha^{-1} d^{-1} for NC67, IA71, IA79, and SC79 crops, respectively, but was 15.9 kg ha^{-1} d^{-1} in the NJ85 study.

Peak P accumulation (Fig. 5) for the lower-yielding IA71, SC79, and IA79 crops was 15.9, 20.7, and 25.0 kg ha^{-1}, respectively. For the higher-yielding NC67, it was 37.9 kg ha^{-1}, and for NJ85, it was 64.7 kg^{1}ha . Maximum rates of P accumulation ranged from 0.4 to 0.7 kg ha^{-1} d^{-1} for the three lower-yielding crops, and 1.0 to 1.7 kg ha^{-1} d^{-1} for the higher-yielding ones. Timely rainfall for the NC67 crop and prevention of drought stress through surface irrigation in the NJ85 study probably increased diffusion rates and contributed to greater P accumulation by those crops.

Potassium accumulation (Fig. 6) ranged from 98 to 150 kg ha^{-1} for the lower-yielding soybean crops, but was 233 kg ha^{-1} for NC67 and 405 kg ha for NJ85. Accumulation rates for K showed more fluctuation for soybean than for either corn

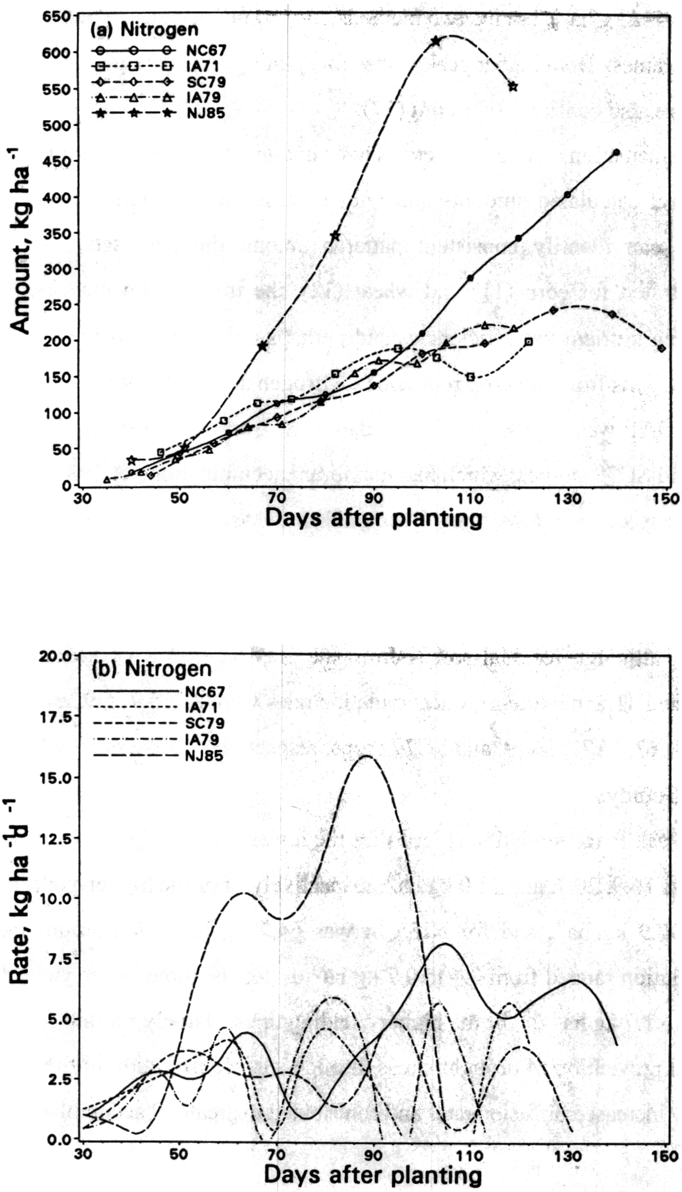


FIGURE 4. Amounts (a) and rates (b) of aerial N accumulation for five soybean data sets.

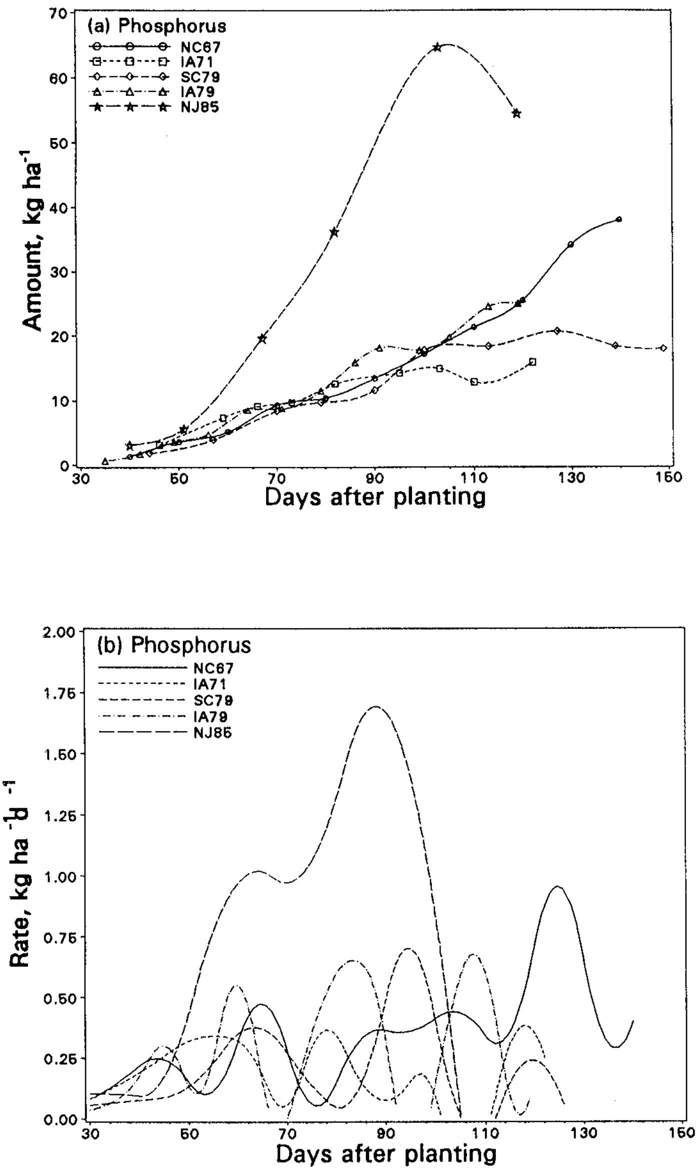


FIGURE 5. Amounts (a) and rates (b) of aerial P accumulation for five soybean data sets.

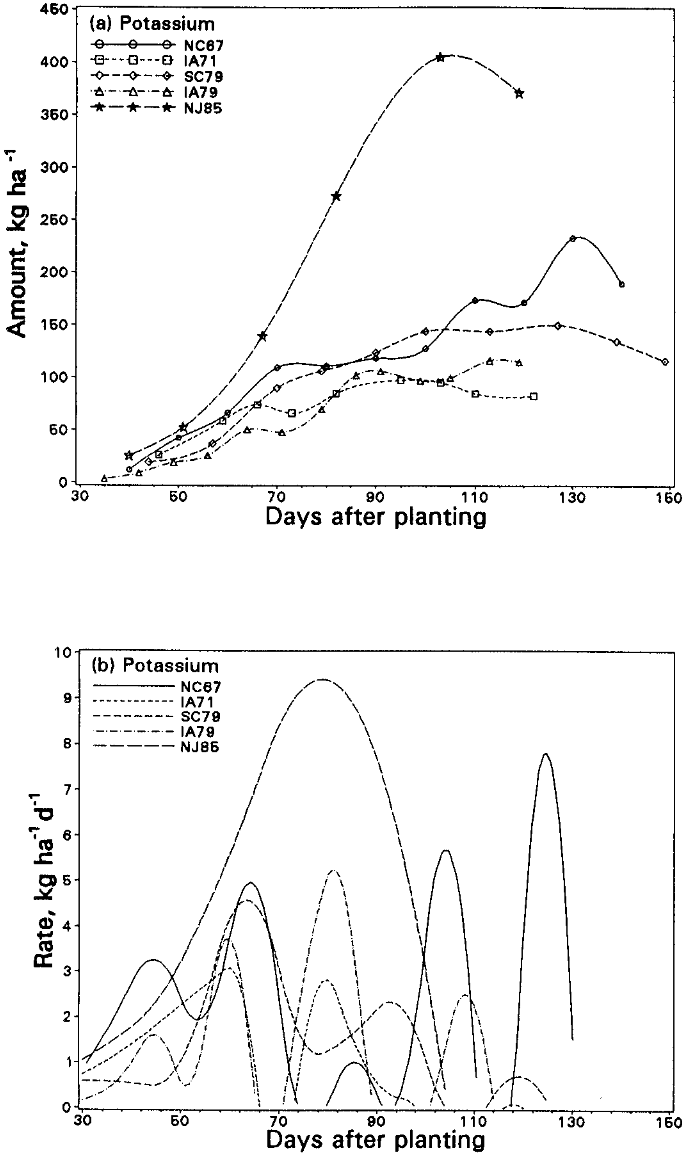


FIGURE 6. Amounts (a) and rates (b) of aerial K accumulation for five soybean data sets.

or wheat (11,12). The graminaceous species consistently accumulated K primarily during vegetative growth stages, with very low K accumulation rates during reproductive stages. Maximum K accumulation rates (3.1 to 18.4 kg ha^{-1} d^{-1}) for soybean generally occurred when pods and seeds were forming. Interactions between K and dinitrogen fixation, as well as transport processes, may have resulted in the species difference.

CONCLUSIONS

Comparison of rates of dry matter and nutrient accumulation by soybean produced several observations. First, aerial dry matter and nutrient accumulation patterns for soybean generally did not show consistent, distinct peaks associated with vegetative and reproductive growth periods as was shown for corn and wheat. Second, the interpolation technique illustrated limitations of the data sets involved and suggested areas where interpretation from their results should be restricted. Finally, the variation demonstrated, through analyses of actual field data such as these, provides a justification for examining the sensitivity of process models to short-term variation on external factors such as water stress or temperature.

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